DESIGN FEATURES OF THE 200 GEV ACCELERATOR

M. Stanley Livingston

November 13, 1968

The accelerator now being designed at the National Accelerator Laboratory will become, when completed, the highest energy machine in the world, producing protons of 200 GeV (and eventually 400 GeV) energy. It is to be located on a 6800 acre farm site near Batavia, Illinois, about 35 miles west of Chicago. The sponsoring organization is the Universities Research Association, a group of 50 universities engaged in high-energy research widely spread across the United States. All supporting funds come from the U. S. Atomic Energy Commission. The project has been authorized by the U. S. Congress and funds are allocated to start the construction this fall. The design staff now occupies existing buildings and recently constructed laboratories on the site, in what was once the village of Weston. The accelerator is scheduled for initial operation in 1972.

The machine is an alternating gradient proton synchrotron of very large orbital radius. It incorporates many new and simplifying features that differ markedly from earlier AG synchrotrons. Acceleration is achieved in three steps: a 200-MeV proton linac about 150-meters long; a fast-cycling 10-GeV "booster" synchrotron of 75-m orbital radius; and a "main ring" synchrotron of 1000-m orbital radius which accelerates the protons to their final energy. The high-energy particles will be ejected at one point in the ring as an emergent beam extending for 3 km, along which will be switching magnets to direct the beam against a sequence of target stations at which research experiments will be performed.

The most significant new feature of the design is the option to increase energy to 400 GeV in the future. This is accomplished by building a main ring of such large radius that magnets will be excited to only half their designed excitation when operating at 200 GeV. Additional power supplies can be added in the future to increase excitation (to 18 kilogauss) and raise particle energy to 400 GeV. Still higher excitation of the magnets can result in energies up to 500 GeV with some reduction in average beam intensity.

The basic time cycle for operation is of 4 sec duration. It starts with a long pulse from the 200-MeV linac sufficient for 3- to 4-turn injection into the booster synchrotron. The booster operates at a repetition rate of 15 per sec. A sequence of 13 cycles (0.8 sec) is used to fill the main ring orbit to a designed intensity of 5×10^{13} protons. Acceleration from 10 GeV to 200 GeV in the main ring extends over 1.6 sec. The magnetic field is then flat-topped at peak energy for a period of up to 1.0 sec, during which the beam is slowly ejected into the emergent beam run for experimental purposes. Then the field is reduced to its injection value in 0.6 sec, and the cycle is repeated. This cycle provides a 25 percent time duty factor for experiments. The average beam intensity is 1.5×10^{13} protons per second, and the beam power at 200 GeV is 480 kilowatts. When operated at 400 GeV each element of the time cycle will be doubled, average beam intensity will be the same, and beam power will be 960 kw.

The Main Ring

The AG magnet system for the main ring consists of separated-function units for bending and focusing. The advantage, for such a large orbit and small aperture, is that the bending magnets that occupy most of the orbit can have flat parallel poles and be excited to much higher flux densities than the shaped poles of AG magnets; this minimizes orbit radius for a given energy. Each normal cell of the magnet lattice is 60 meters long, has one focusing (F) and one defocusing (D) quadrupole, two bending magnets (B) and two short field-free regions (O), in a FOBDOB sequence. Bending magnets are the longest units and occupy 75% of the orbit; the quadrupoles needed to provide focusing (number of betatron wavelengths around the orbit = 20.25) are shorter and occupy 8% of the orbit. The remaining 17% of the orbit consists of the short field-free regions (O), in the normal cells, six medium straights each of 20-m length, and six long straights each of 50-m length. These straight sections are used for injection and ejection of beams, radio-frequency acceleration, vacuum manifolds, control and sensing devices, etc.

The beam emittance from the booster synchrotron at 10 GeV is small, so small beam apertures are acceptable in the main ring, with maximum dimensions of about 5 x 12 cm. A bending magnet (B) is formed of four straight units each 6 m long and supported inside a box girder. These units are of two types, having 1-1/2 in. and 2 in. pole gaps; this feature takes advantage of the smaller vertical aperture requirement adjacent to F quadrupoles. The iron cores are formed of punched laminations of the classic "H" shape, with enlarged windows for the excitation coils. The number of turns for the two types are in the ratio 12:16, so they can be powered in series. Coils are formed of pierced copper, are water-cooled, and occupy the entire window area of the cores. The magnetic efficiency (ratio of magnetic field intensity to ampere-turns) measured in model studies is found to be 96% at 18 kg (400 GeV).

The quadrupole magnets are also formed of punched laminations, with external dimensions similar to the bending magnets, but with 4 poles and 4 sets of water-cooled coils. Each quadrupole is 2 m long and produces a maximum field gradient of 125 kg/meter (at 200 GeV) or 250 kg/m (at 400 GeV).

Separate power supplies are used for the bending and focusing magnets, and are scheduled to follow the acceleration cycle in phase. A system of tubular conductors distributes both water and power to the magnets around the ring. The bending magnets are in a series circuit powered by 24 rectifier systems spaced around the ring, to reduce volts-to-ground insulation. A separate bus system distributes power to the quadrupoles, which also form a single series circuit. The magnets are cycled from injection field to maximum field every 4 sec. The peak power is 54 Mw and the average power 16 Mw (at 200 GeV). Motor generator-flywheel systems will not be used to power the magnet as in previous AG synchrotrons, but the power will be taken directly from the AC power mains, using solid-state rectifier controls to obtain the desired dc cycle from the 3-phase, 60-cycle mains. Reactive components will be switched into the circuit during the cycle to control power factor.

Booster Synchrotron

The booster accelerates protons injected from the linac at 200-MeV energy up to 10-GeV energy for injection into the main ring, at a rate of 15 per sec. A sequence of 13 booster pulses is used to fill the orbit of the main ring. For this fast-cycling machine, magnet core laminations are thinner and conductors smaller than for the main ring. The required beam apertures are slightly larger. A combined-function system of AG units is used, arranged in a FODO lattice pattern, primarily to provide accurate tracking of the bending and focusing functions. The AG magnet units are assembled in curved sectors to match the beam curvature in the orbit.

The ac magnet power comes from a distributed resonant system of capacitors and inductors mounted within the box girders that support the magnets, resonant at 15 Hz. A dc bias supplied to all magnets in series provides a sine-wave excitation varying from zero to maximum field. Total power including distributed system losses is about 3 Mw.

The linac beam is brought over the booster ring and down to the central plane on the inside of the ring, where 3- to 4-turn radial injection provides a beam for acceleration of 3.8×10^{12} protons per pulse. Following acceleration of each pulse the beam is ejected vertically in one-turn and transported to the injection straight section of the main ring, where it is injected in the vertical plane. The single-turn extraction efficiency from the booster is designed to be about 95%.

The Linac

A linear accelerator provides protons of 200-MeV energy for injection into the booster synchrotron. Protons for injection into the linear accelerator are preaccelerated to 750-keV by a Cockcroft-Walton dc generator. High voltage supplies of this type are commercially available. The design and performance parameters of the linac are essentially the same as for the 200-MeV injector linac now being constructed at the Brookhaven National Laboratory. An output current of 100 ma or more can be achieved, with pulse lengths up to 100 μsec duration, well in excess of that needed for multi-turn filling of the booster.

The linac is made of 9 cylindrical cavities, each 1-m in diameter and 16 m long. Within each cavity is a linear array of drift tubes designed to be resonant at 201.25 MHz Radiofrequency power is supplied to each cavity by an RCA superpower triode. The total peak rf power is 37 Mw and the average excitation power 110 kw. Quadrupole magnets are placed within each drift tube to focus the proton beam during acceleration. The linac is operated at 15 pulses per second, timed to fill the booster orbit on each booster cycle.

The linac is to be housed within a shielded enclosure of 14 x 12.5 ft dimensions; a 2-ton crane is provided to handle equipment. A parallel equipment bay outside the shielding provides space for power supplies.

Both the linac and booster are operated on the short duty cycle required to fill the main ring at 4-sec intervals. No provision is made for utilizing either of the pre-accelerators for experiments during the unused portions of the cycle.

Radiofrequency Acceleration

The radiofrequency systems for both the booster and the main ring use resonant cavities operating at about 50 MHz, with the frequency modulated to match particle velocity by means of ferrite tuners. The frequency in the booster changes from 30.26 MHz at injection (200 MeV) to 53.24 MHz at 10 GeV. During acceleration in the main ring this frequency increases to 53.44 MHz. The bunched beam from the booster is transferred synchronously into the main ring, maintaining the synchronous bunching.

In the booster a total of 18 cavities are symmetrically spaced around the orbit, each 2.4-m long, providing a total peak voltage per turn for acceleration of 850 kV. Each cavity contains two accelerating gaps, and is tuned by a set of ferrite-loaded stems. Losses in the ferrite (total weight 11 tons) dominate the power requirement, which is 1 Mw peak during the pulse.

In the main ring 16 rf cavities are grouped in one medium straight section, with a total length of 20 m, which provide a total peak voltage per turn of 4.7 MV during the 1.6-sec acceleration interval. Due to the small frequency swing, the ferrite tuners for these cavities are removed to the radiofrequency power and equipment building located outside the main ring shielding. The power required for acceleration of the beam is the dominant factor; total rf power during the pulse is 1.2 Mw.

In both accelerators, signals derived from the circulating beam are used to control the phase and amplitude of the accelerating voltage.

Vacuum System

The design pressure within the main-ring vacuum chamber is 1×10^{-7} torr, to reduce loss of beam due to gas scattering to less than 0.1% during the acceleration cycle. The all-metal welded chamber is formed of thin-walled stainless steel tubing of oval cross section fitting between magnet pole faces. Pump manifolds are located in the 1-ft spacings between the straight magnet sectors. Chamber sections terminate in circular flanges which can be welded or disconnected for replacement by automatic welding and grinding machinery. Titanium-discharge sputter-ion pumps of 50 liter/sec capacity are located at manifolds with an average spacing of 15 m. Roughing pumps (mechanical plus turbomolecular) located in utility buildings spaced around the ring are connected by manifolds and valves at frequent intervals, and are designed to pump down the chamber to 2×10^{-6} torr in 1 hour. Model sections of chamber have been tested with the planned pump spacing and the design pressure has been achieved.

The vacuum system of the booster is designed to achieve 5×10^{-7} torr, since gas scattering is of less concern in the short acceleration cycle. This fast-cycling synchrotron requires a very thin chamber wall (if of metal) or alternatively a ceramic chamber with metal coating. Titanium pumps rated for 100 liter/sec are connected by manifolds between each magnet sector. Rough vacuum equipment is located in the equipment gallery outside the shielded enclosure.

Enclosures and Shielding

The main synchrotron is housed in an underground circular tunnel-type enclosure of 1000 m radius. Floor level is 5 m below average ground level; earth fill over the tunnel will provide radiation shielding. The tunnel cross section is 10 ft wide and 8 ft high, formed of precast concrete sections sealed to a concrete slab floor. No crane is used, but magnet components will be installed using special handling vehicles. Magnets are mounted close to the outside wall of the enclosure, providing a service aisle of 7-ft width. The magnets are mounted on adjustable stands directly on the concrete slab floor; no special foundations will be used. Electrical and water services are mounted on the tunnel wall above the magnets.

A survey system of stretched wires mounted on the support piers extends around the ring, and provides a base grid for the magnet installation. With the ring complete, beam sensing electrodes will provide information for precise adjustments.

At each short straight section (O) in the magnet lattice, the tunnel is enlarged to 12-ft width and 9-ft height, for mounting of special devices and for utility cross-overs from utility houses spaced around the inside of the ring. The same enlarged enclosures are used for most of the medium- and long-straights. One medium-straight is used for rf acceleration, paralleled by an external radiofrequency power building; one long-straight is enlarged into a transfer bay where beam from the booster is injected and the emergent beam is ejected, also paralleled by a support gallery outside the shielding. Other straight sections will be developed for special purposes as needed.

Special vehicles will be developed for installing accelerator components in the enclosure and for performing maintenance operations. Remote-handling vehicles may be used for routine operations or special functions. In general, the use of shielded vehicles for use by maintenance personnel is not anticipated.

Radiation shielding consists primarily of earth fill above the underground enclosures, with greater thickness opposite inhabited areas or buildings. The shielding is designed to protect resident personnel from acquiring exposures exceeding 0.1 the safe exposure rate for radiation workers. The primary radiation hazard will be exposure of personnel entering the enclosures to induced radioactivity developed by beam spills. The basic policy is to limit beam spills by control of beam intensity, until development can reduce the percentage of spill at each critical location or the induced radioactivity can be controlled by special shielding. Local "hot spots" will develop around injection and ejection devices, clean-up targets, etc., but the enclosure between these regions should be relatively "cool".

Other undergound and shielded enclosures house the linac and the booster synchrotron. General laboratory buildings and working space for office personnel are provided in other structures. The dominant building on the site will be the 12-story general office and laboratory, centrally located but removed from any radiation hazards.